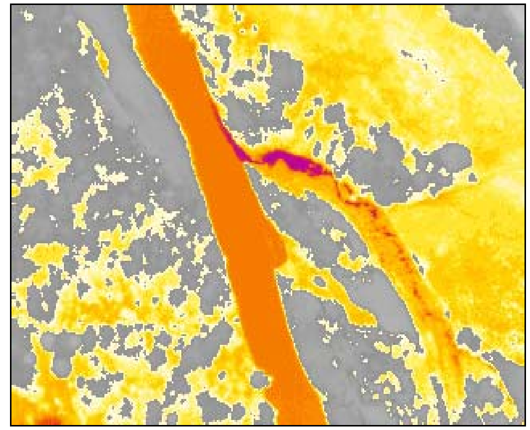
Aerial Survey of Naches River, WA

Thermal Infrared and Color Videography



Report to:

Washington State Department of Ecology
Environmental Assessment Program
P.O. Box 47600, Olympia, WA 98504-7600

By:

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Survey Date: August 14, 2004

Final Report

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Background

In 2004, The Washington State Department of Ecology contracted with Watershed Sciences, Inc. to conduct an airborne thermal infrared (TIR) survey of the Naches River, WA. The objective of the project was to exemplify the thermal characteristics of the river and to document surface water inflows and areas of potential sub-surface upwelling. The results are intended to provide a better understanding of the hydrology of the basin. The data are also intended to support the Washington DOE Temperature TMDL process.

Water temperatures vary naturally due to topography, channel morphology, substrate composition, riparian vegetation, ground water exchanges, and tributary influences. Stream temperatures are also affected by human activities within the watershed. TIR images provide information about spatial stream temperature variability and can illustrate changes in the interacting processes that determine stream temperature. In most cases, these processes are extremely difficult to detect and quantify using traditional ground-based monitoring techniques.

The imagery and derived data are contained in an associated geographic information system (GIS) database. This report provides a detailed description of the work performed, including methodology and quantitative assessments of data quality. In addition, the report presents and discusses the spatially continuous longitudinal temperature profiles derived from the imagery. These profiles provide a landscape scale perspective of how temperatures vary along the stream gradient and are the basis for follow-on analysis. Sample images are also contained in this document. The images illustrate some of the thermal features, channel characteristics, and hydrologic processes discussed in the report. The images are not meant to be comprehensive, but provide examples of image scenes and interpretations contained in the database associated with this report.

Methods

Data Collection

Instrumentation: Images were collected with TIR (8-12μ) and visible-band cameras attached to a gyro-stabilized mount on the underside of a helicopter. The two sensors were aligned to present the same ground area, and the helicopter was flown longitudinally along the stream channel with the sensors looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer in a format in which each pixel contained a measured radiance value. The individual images were referenced with time and position data provided by a global positioning system (GPS).

Sensor mount used for the Naches River TIR and color video surveys.

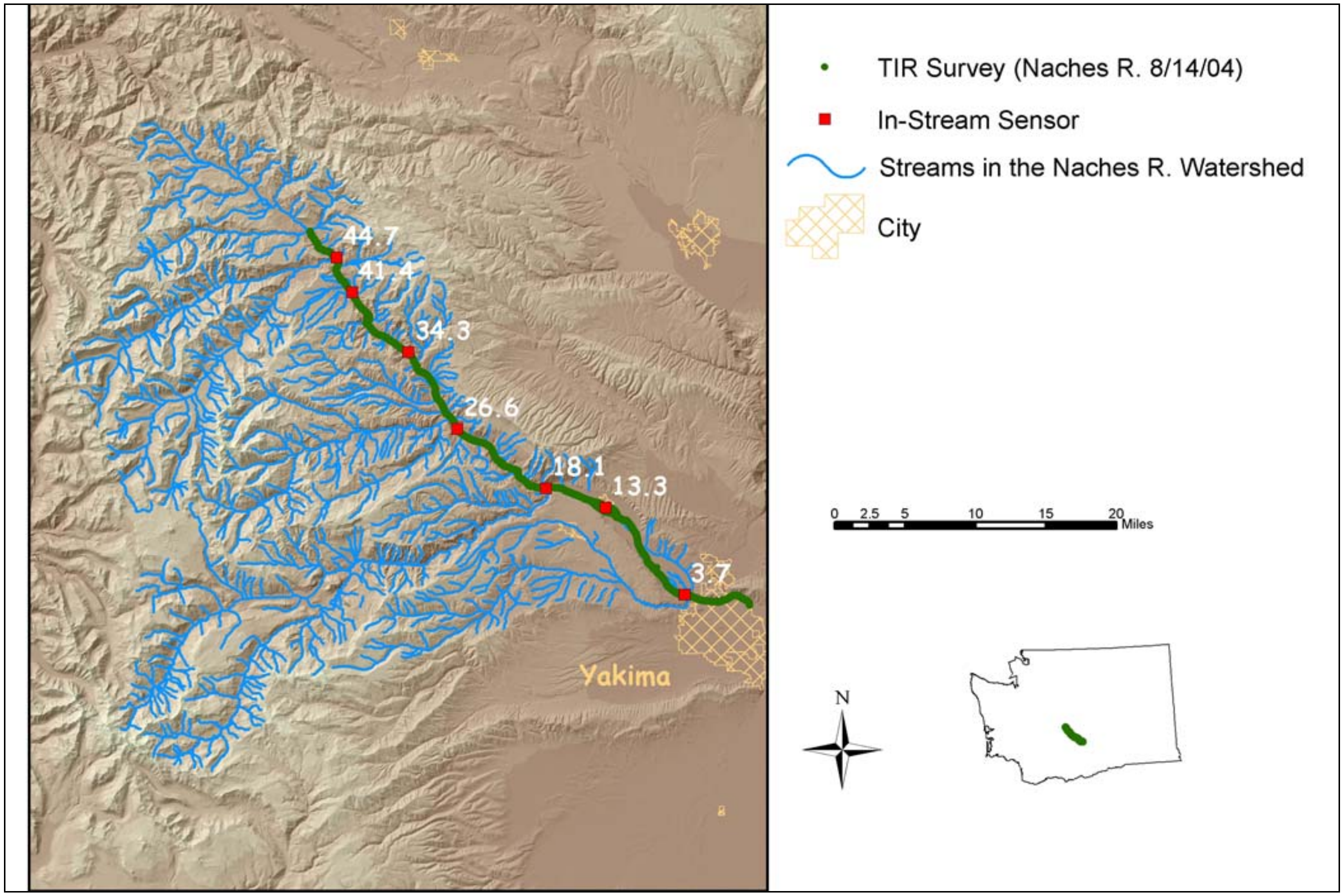
Flight Parameters: The survey of the Naches River was conducted from the confluence of the Little Naches River and the Bumping River, downstream to its confluence with the Yakima River. The river was surveyed from 2500 ft above ground level (AGL) in order to capture the many features of the river, including springs, tributaries, and segments of the river with multiple mainstream channels. The survey was conducted on August 14, 2004 between 1:55 PM and 3:15 PM.

Two forest fires were active in the region during the week of August 14, resulting in two temporary flight restrictions (TFRs) over large portions of the Naches River basin. The Mud Lake fire was within 2 miles of the Naches River and was fought actively from the air until August 13. Watershed Sciences coordinated the TIR river survey with USFS fire managers and received approval for operating within the TFR boundary prior to the mission. The fires did not result in any smoke over the river during the time span of the TIR survey. However, the fires prohibited collecting the TIR data earlier in the week.

Image Characteristics: Images were collected sequentially with 40% or greater vertical overlap. On the Naches River survey, the TIR images presented a ground width of approximately 270 meters with a spatial resolution of ~0.84 meters.

Ground Control: Watershed Sciences deployed in-stream data loggers prior to the flight in order to ground truth (i.e. verify the accuracy of) the TIR data. The data loggers were placed at access points throughout the watershed with at least one instrument deployed every ten river miles. The distribution of the in-stream data loggers allowed for checking radiant temperatures at regular intervals over the duration of the survey. Meteorological data including air temperature and relative humidity were recorded in the basin using a portable weather station (*Onset*) located at the Highway 12 bridge over the Naches River.

Study Area

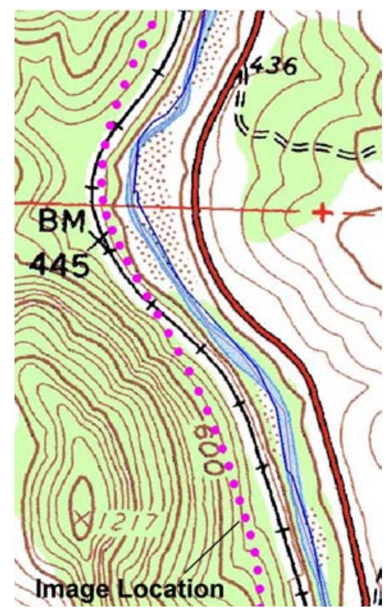


TIR Survey (Naches R. 8/14/04)
In-Stream Sensor
Streams in the Naches R. Watershed
City
44.7
41.4
34.3
26.6
18.1
13.3
3.7
Yakima
0 2.5 5 10 15 20 Miles
N

Data Processing

Calibration: Measured radiance values contained in the raw TIR images were converted to temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor. The atmospheric transmission value was modeled based on the air temperatures and relative humidity recorded at the time of the survey. The radiant temperatures were then compared to the kinetic temperatures measured by the in-stream data loggers. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location. Calibration parameters were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Image showing TIR image points plotted over a USGS 1:24K topographic map. Each point represents a TIR and color video image pair acquired at that location.



Interpretation and Sampling: Once calibrated, the images were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file. The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images.

Geo-referencing: The images are tagged with a GPS position at the time they are acquired. Since the TIR camera is maintained at vertical down-look angles, the geographic coordinates provide an accurate index to the location of the image scene. Due to the relatively small footprint of the imagery and independently stabilized mount, image pixels are not individually registered to real world coordinates. In order to provide further spatial reference, the TIR images were assigned a river mile based on a routed stream layer.

Temperature Profiles: The median temperatures for each sampled image were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns.

Thermal Image Characteristics

Surface Temperatures: Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed; however, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow and can usually be detected in the imagery. Occurrences of thermal stratification interpreted during analysis are identified in the results section for the survey.

Expected Accuracy: Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (~ 4 to 6%). During calibration, a correction is included to account for average background reflections. However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.6°C (Torgersen et al. 2001[1]). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.6°C are not considered significant unless associated with a surface inflow (e.g. tributary).

Differential Heating: In stream segments with flat surface conditions (i.e. pools) and relatively low mixing rates, observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike with thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed.

Feature Size and Resolution: A small stream width logically translates to fewer pixels "in" the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures (Torgersen et. al. 2001). In some cases, small tributaries were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample.

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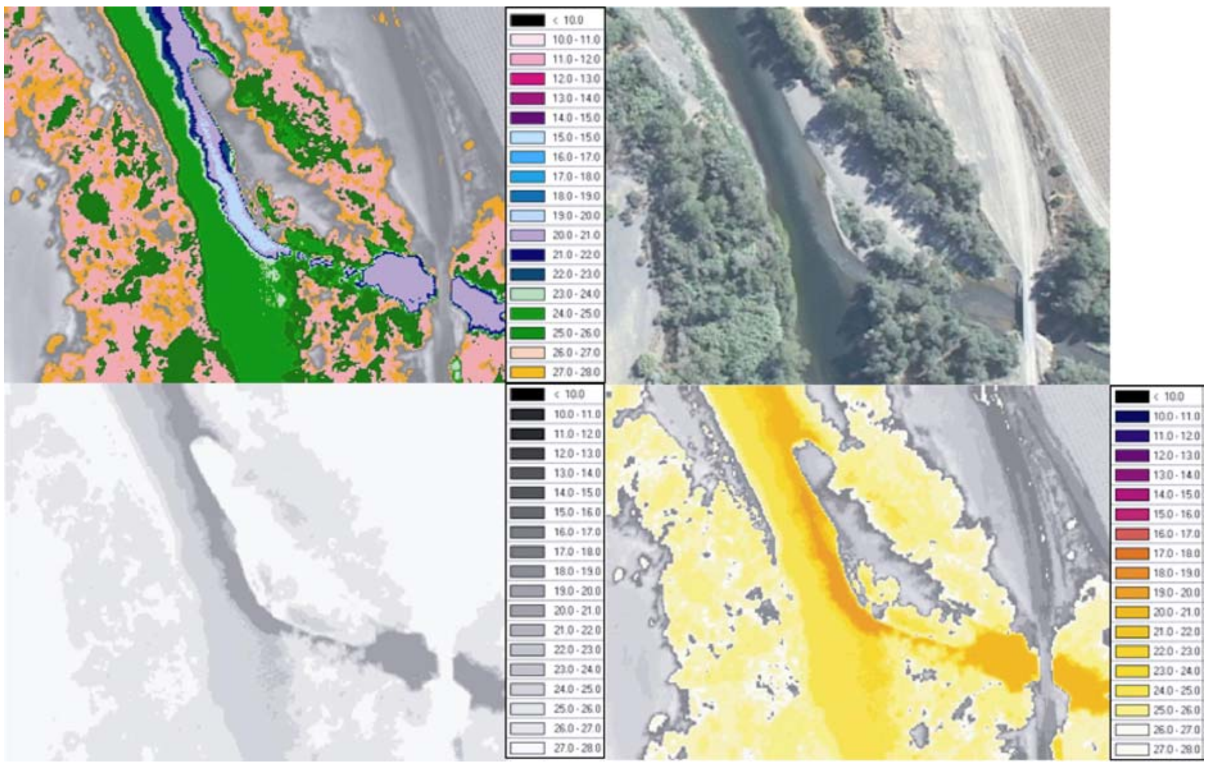
[1] Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

<u>Temperatures and Color Maps:</u> The TIR images collected during this survey consist of a single band. As a result, visual representation of the imagery *(in a report or GIS environment*) requires the application of a color map or legend to the pixel values. The selection of a color map should highlight features most relevant to the analysis (i.e. *spatial variability of stream temperatures*). For example, a continuous, gradient style color map that incorporates all temperatures in the image frame will provide a smoother transition in colors throughout the entire image, but will not highlight temperature differences in the stream. Conversely, a color map that focuses too narrowly cannot be applied to the entire river and will "washout" terrestrial and vegetation features. The method used to select a color map for the report images attempts to accomplish both. The map is based on using discrete colors to represent the range of water temperatures observed during the analysis based on 1^{o}C or 0.5^{o}C increments and a linear gray scale to represent temperatures above the maximum observed water temperature. The images below provide an example of three different color maps applied to the same thermal image.



Results

Weather Conditions

On August 14, weather conditions were fair in the morning with mostly blue skies over the lower basin. Clouds were present on the ridges in the morning, but built over the Naches River valley by mid-afternoon. Air temperatures were slightly cooler than previous days with the maximum 90.2^{o}C recorded at 3:00 PM. The weather quality deteriorated during the survey with some light rain in Yakima noted shortly after the conclusion of the survey. Weather forecasts for the region for the evening of August 14 and the following days were for thunderstorms with heavy rains.

Time	Air Temp (F)	Air Temp (C)	Relative Humidity (%)
8/14/04 @ Highway 12 Bridge			
12:00	81.5	27.5	31.8
12:30	82.2	27.9	35.7
13:00	85.1	29.5	27.1
13:30	88.0	31.1	28.9
14:00	85.8	29.9	29.9
14:30	85.1	29.5	24.3
15:00	90.2	32.3	17.8
15:30	89.5	31.9	19.9
16:00	88.7	31.5	19.9
16:30	88.7	31.5	20.4
17:00	87.3	30.7	23.9
17:30	83.0	28.3	36.7
18:00	78.0	25.6	49.4

Thermal Accuracy

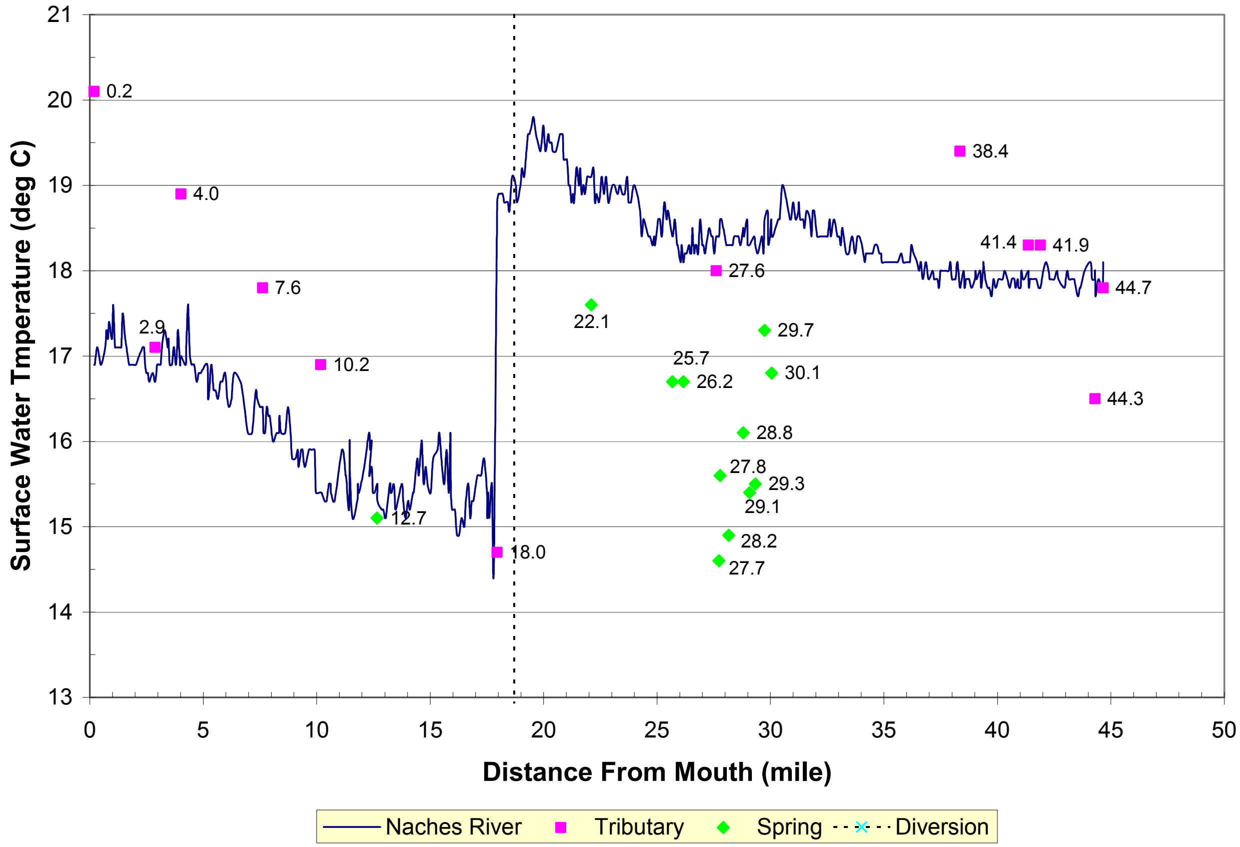
The table below summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. The average absolute temperature accuracies were within the desired accuracy of ±0.5°C. The range of temperature differences was also consistent with those observed during other surveys conducted in the region over the past six years.

Image	Time	Mile	Kinetic (°C)	Radiant (°C)	Difference (°C)
Naches River 8/14/04 (Avg Abs Diff = 0.3°C)					
nac0135	14:00	44.7	17.8	18.3	-0.5
nac0278	14:05	41.4	17.9	17.8	0.1
nac0517	14:13	34.3	18.4	18.3	0.1
nac0839	14:23	26.6	18.7	18.4	0.3
nac1258	14:37	18.0	19.3	18.9	0.4
nac1489	14:45	13.3	15.1	15.1	0
nac2192	15:09	3.7	16.6	17.1	-0.5

Naches River

Longitudinal Temperature Profile

The figure below illustrates the median sampled temperatures plotted versus river mile for the Naches River from the confluences of the Little Naches and Bumping Rivers to the mouth of the Naches River. Tributaries and other sampled inflows (i.e. springs/seeps) are labeled on the profile by river mile and summarized in the table on the next page.



Tributaries, surface springs, and other detected surface inflows

Tributary	Image	km	mile	Tributary °C	Naches R. °C	Difference °C
Tributary Name						
Bumping River (RB)	nac0147	71.9	44.7	17.8	18.1	-0.3
Milk Creek (LB)	nac0167	71.3	44.3	16.5	18.0	-1.5
Devil Creek (RB)	nac0261	67.4	41.9	18.3	17.8	0.5
Swamp Creek (RB)	nac0280	66.6	41.4	18.3	18.0	0.3
Pond Outlet (LB)	nac0387	61.7	38.4	19.4	17.8	1.6
Rattlesnake Creek (RB)	nac0807	44.4	27.6	18.0	18.4	-0.4
Tieton River (RB)	nac1260	28.9	18.0	14.7	18.8	-4.1
Penstock Powerhouse Outlet (LB)	nac1842	16.4	10.2	16.9	15.4	1.5
Unnamed Tributary (RB)	nac1949	12.3	7.6	17.8	16.4	1.4
Unnamed Tributary (LB)	nac2180	6.5	4.0	18.9	17.0	1.9
Cowiche Creek (RB)	nac2223	4.6	2.9	17.1	16.7	0.4
Yakima River (LB)	nac2312	0.3	0.2	20.1	16.9	3.2
Spring						
Spring (RB)	nac0716	48.4	30.1	16.8	18.4	-1.6
Spring (RB)	nac0736	47.9	29.7	17.3	18.6	-1.3
Spring (LB)	nac0750	47.2	29.3	15.5	18.3	-2.8
Spring (RB)	nac0757	46.8	29.1	15.4	18.3	-2.9
Spring (LB)	nac0768	46.4	28.8	16.1	18.5	-2.4
Spring (RB)	nac0791	45.3	28.2	14.9	18.3	-3.4
Spring (LB)	nac0803	44.7	27.8	15.6	18.6	-3.0
Spring (RB)	nac0805	44.6	27.7	14.6	18.4	-3.8
Spring (RB)	nac0856	42.1	26.2	16.7	18.1	-1.4
Spring (MID)	nac0873	41.3	25.7	16.7	18.4	-1.7
Spring (LB)	nac0980	35.6	22.1	17.6	19.1	-1.5
Spring (LB)	nac1729	20.4	12.7	15.1	15.5	-0.4

Observations and Analysis

Water temperatures in the Naches River exhibited a high degree of thermal variability across different spatial scales. At the basin scale, the predominant feature was the inflow of the Tieton River (mile 18.0), which had a dramatic impact on the stream temperatures over the lower 18 miles. The thermal influence of the Tieton River contributed more to lower temperatures at the mouth of the Naches (~17.0°C) than at the confluence of the Little Naches and Bumping Rivers (mile 44.7). The longitudinal profile illustrates differences in heating rates along the stream gradient, which allows segmentation of the profile into reaches with similar thermal characteristics. The following paragraphs discuss these reaches individually.

<u>Mile 44.7 – 36.6 (*consistent temperatures*):</u> At their confluence, the Little Naches and the Bumping River were essentially the same temperature (~18.0°C) at the time of the survey and temperatures remained consistent in the first 8.1 miles of the Naches River (17.9°C ±0.2°C). Four tributary inflows were detected through this reach, but did not alter the prevailing longitudinal temperature pattern. The stream channel through this reach was relatively confined (*Hwy 410 and terrain*) compared to areas downstream. None-the-less, multiple channels and large gravel bars were common features within this reach. These features often suggest hyporheic flow as a buffer to heating processes. However, springs or seeps, which provide indicators of these processes, were not detected in the imagery within this reach. Cloudy conditions near the upstream end of the survey reduced thermal loading and may have diminished the normal heating process. The combination of thermodynamic processes contributing to spatial temperature patterns in this reach was not directly apparent from the TIR imagery.

<u>Mile 36.6 – 30.5 (*gradual downstream warming*):</u> Stream temperatures exhibited a slight warming trend within this reach with temperatures gaining ~1.1°C. Although temperatures increased, the gain was not dramatic. The gradual downstream heating suggests an alternation in the balance of hydrologic and thermodynamic processes that maintained temperatures in the upstream reach.

<u>Mile 30.5 – 26.0 (*slight cooling, with local thermal variability*):</u> A total of nine sub-surface discharges were detected within this reach. Most of these discharges were floodplain spring brooks and seeps (*reference sample imagery*). A review of the topographic base map shows that this reach begins upstream of the town of Nile, where the river enters a lower gradient, less confined reach. The imagery shows a general increase in channel complexity with multiple side channels and large alluvial gravel bars. Overall, the longitudinal profile shows a slight decrease in water temperatures through this reach.

<u>Mile 26.0 – 19.6 (*increased downstream heating*):</u> Water temperatures increased from 18.1°C to a survey maximum of 19.8°C through this reach. Although temperatures generally increased, two small sub-surface discharges were sampled within this reach and the profile shows some local variability in the general pattern. This reach begins at the downstream end of the Nile valley and inspection of the imagery shows a less complex, more confined channel.

Mile 19.6 – 10.6 (*cooling and local thermal variability*): At ~1.5 miles upstream of the confluence of the Tieton River, water temperatures in the Naches dropped by ~1.0°C. Although no cooling sources were detected, the location corresponds to the upper Naches Valley and a distinct transition in the morphology for the river. The Selah Valley Canal diversion was observed at river mile 18.7. The canal diversion occurred ~0.7 miles upstream of the Tieton River, so the downstream effects of the diversion on heating rates was not directly apparent from the imagery. At river mile 18.0, the Tieton River contributed water that was 4.1°C cooler than the mainstream, and caused a 3.4°C drop in temperatures in the Naches River from 18.7°C to 15.3°C. Downstream of the Tieton River confluence, stream temperatures varied locally between 14.9°C and 15.1°C, but the source of variability was not apparent from the TIR imagery.

Mile 10.6 – 0.0 (*gradual downstream warming*): Over the lower 10.6 river miles, water temperatures in the Naches showed a general warming trend gaining ~3.0°C. Four tributary inflows were detected in this reach and each contributed warmer water to the main stem. No sub-surface discharges were detected in this reach. At its confluence, the Naches River was a cooling source to the Yakima River.

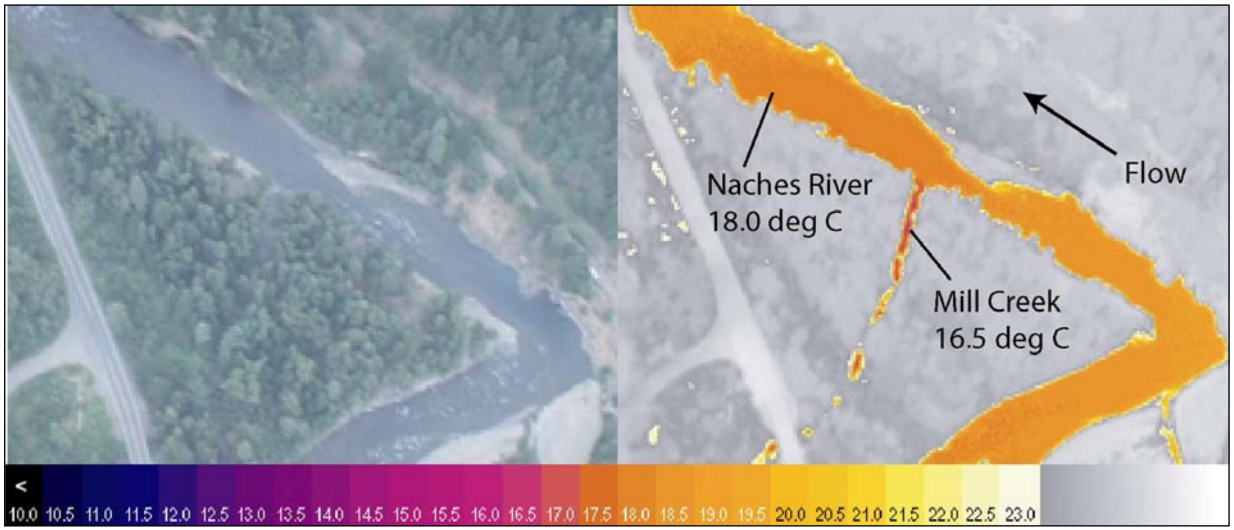
The delineation of these reaches was based solely on visual inspection of the longitudinal temperature profile and used for the purpose of discussion. Other segmentations are possible at different spatial scales by including other spatially explicit data sets.

Digital photo of the Naches River Valley taken from the window of the aircraft.

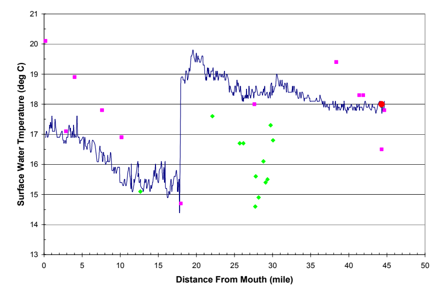
Sample Images

The following pages contain images from the survey of the Naches River including a brief discussion. The location of the site along the longitudinal temperature profile is also illustrated.

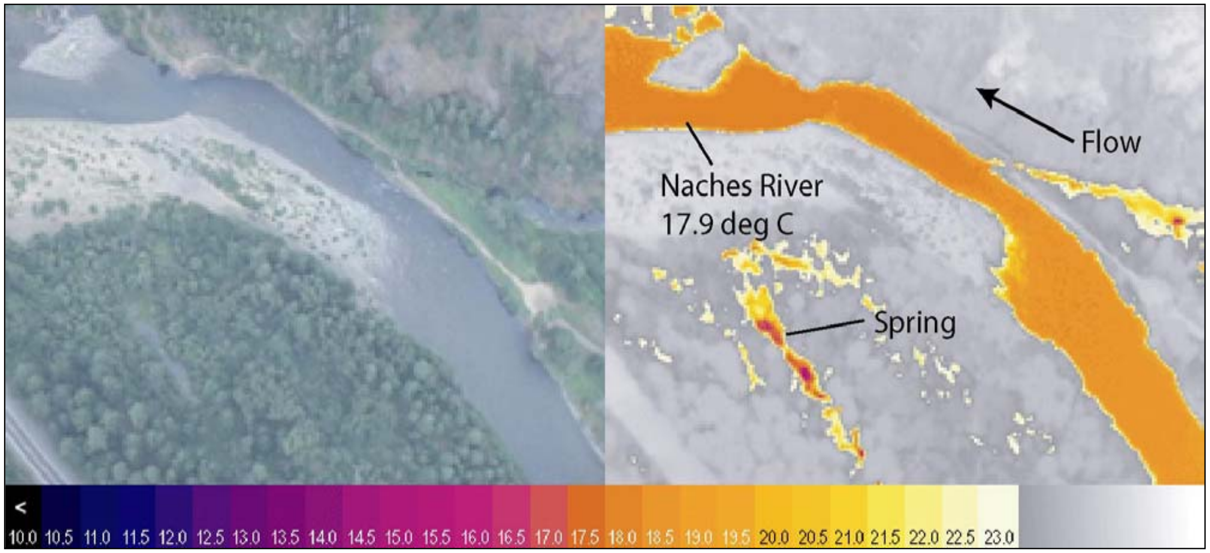
Milk Creek Confluence (river mile 44.3)



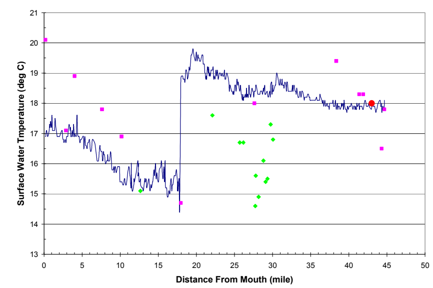
This image pair shows the confluence of Mill Creek (16.5°C) on the left bank of the Naches River (18.0°C) at river mile 44.3. Mill Creek enters just downstream of the start of the Naches River at the confluence of the Little Naches and Bumping Rivers.



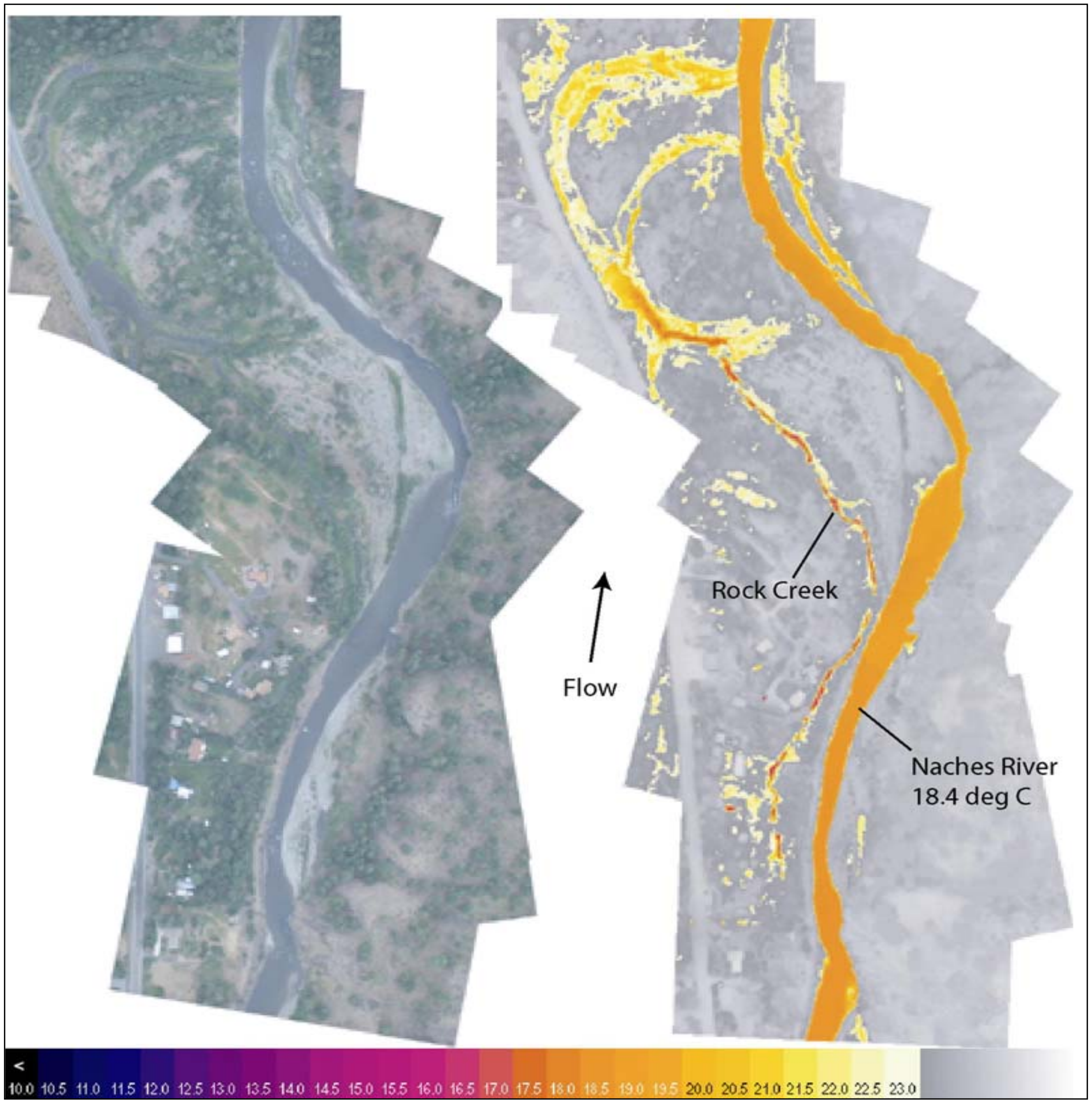
Spring (river mile 43.0)



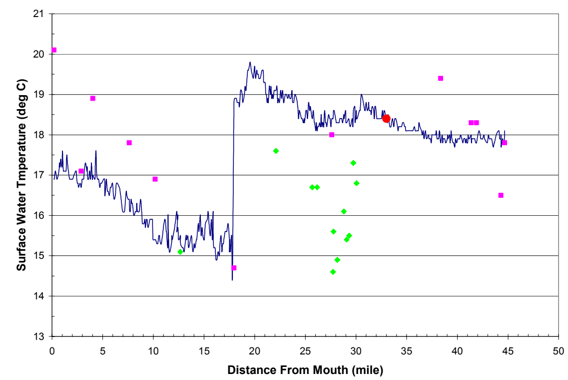
This image pair shows cool water emerging within the floodplain of the Naches River (17.9°C) at mile 43.0. Although the spring does not show an obvious surface discharge into the river and was not sampled, the detection of cooler water within the floodplain suggests an area of sub-surface upwelling.



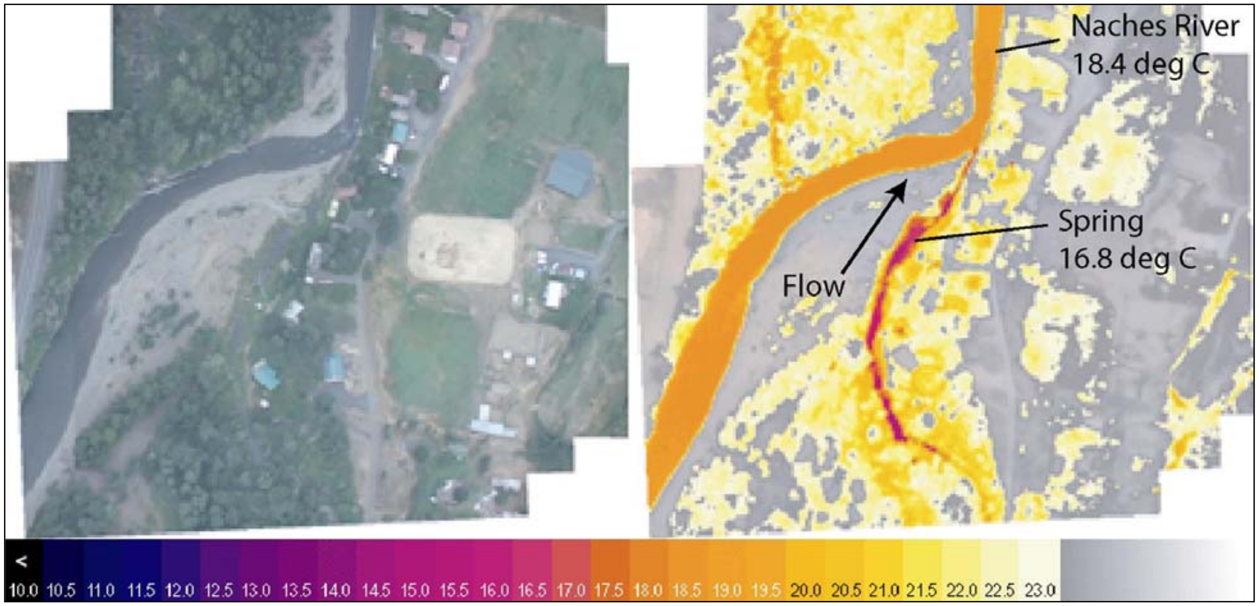
Rock Creek Confluence (river mile 33.0)



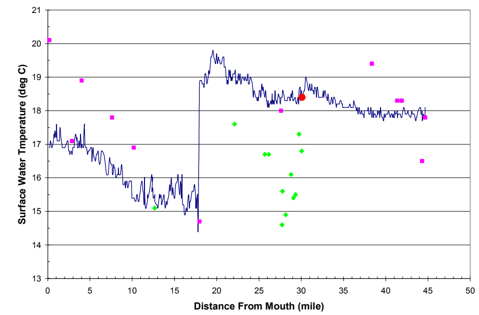
This image pair shows the presence of Rock Creek (16.8°C) along the left bank of the Naches River (18.4°C) at river mile 33.0. Rock Creek was not sampled because there was no direct surface connection to the main stem. However, the imagery provides an example of the channel complexity and local temperature variability observed in this reach.



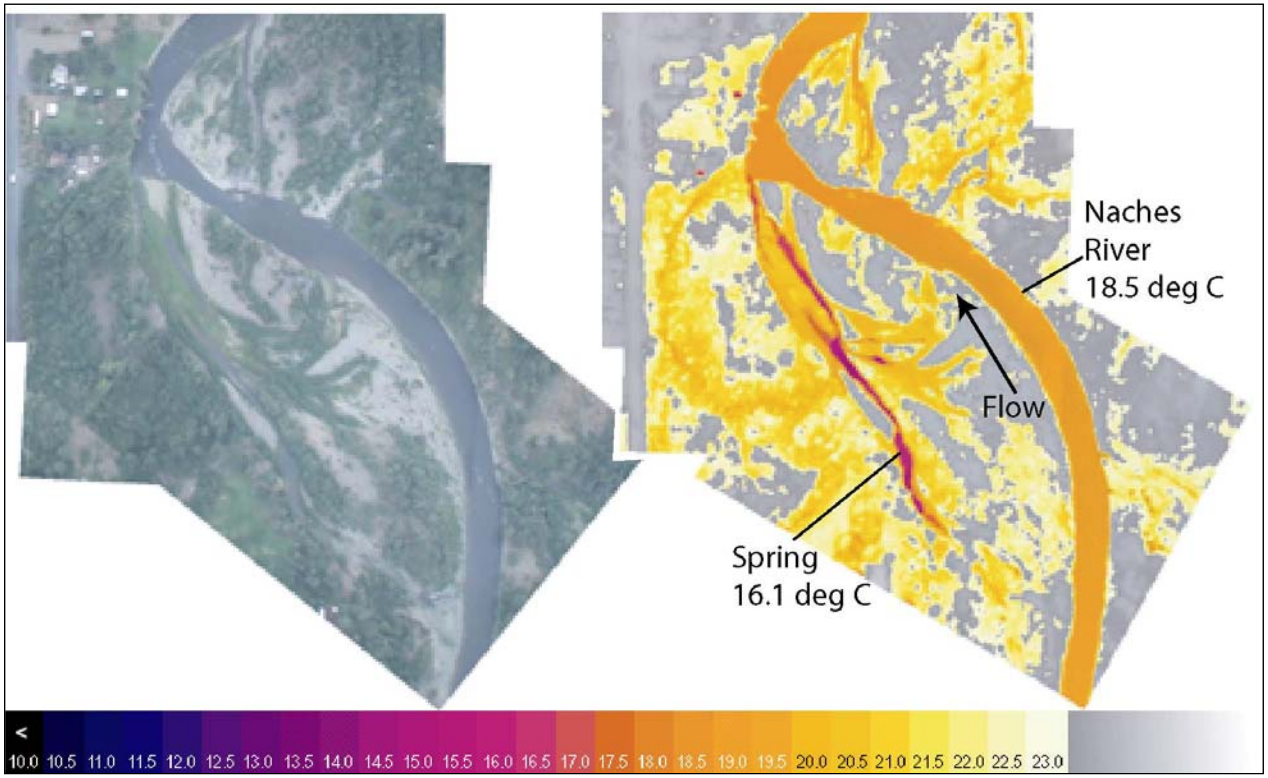
Springs (river miles 26.2 – 30.1)



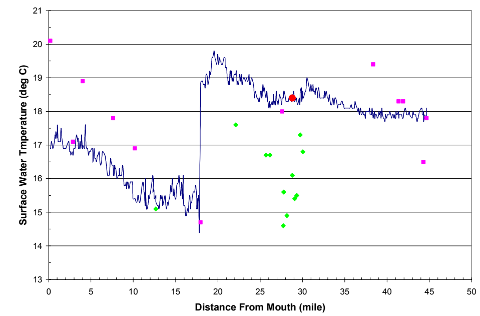
This image pair shows a floodplain spring brook (16.8°C) on the right bank of the Naches River (18.4°C) at river mile 30.1. This type of discharge was common in this reach.



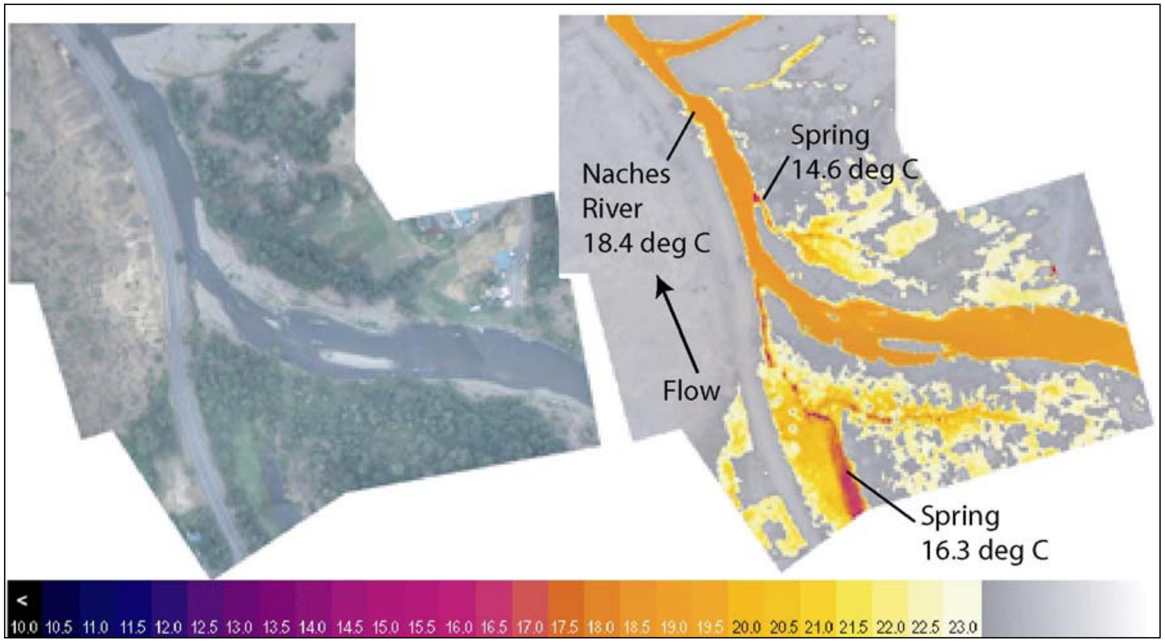
Spring (river mile 28.8)



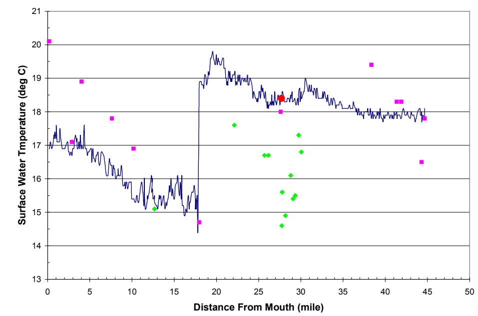
This image pair shows a spring (16.1°C) along the left bank of the Naches River (18.5°C) at river mile 28.8.



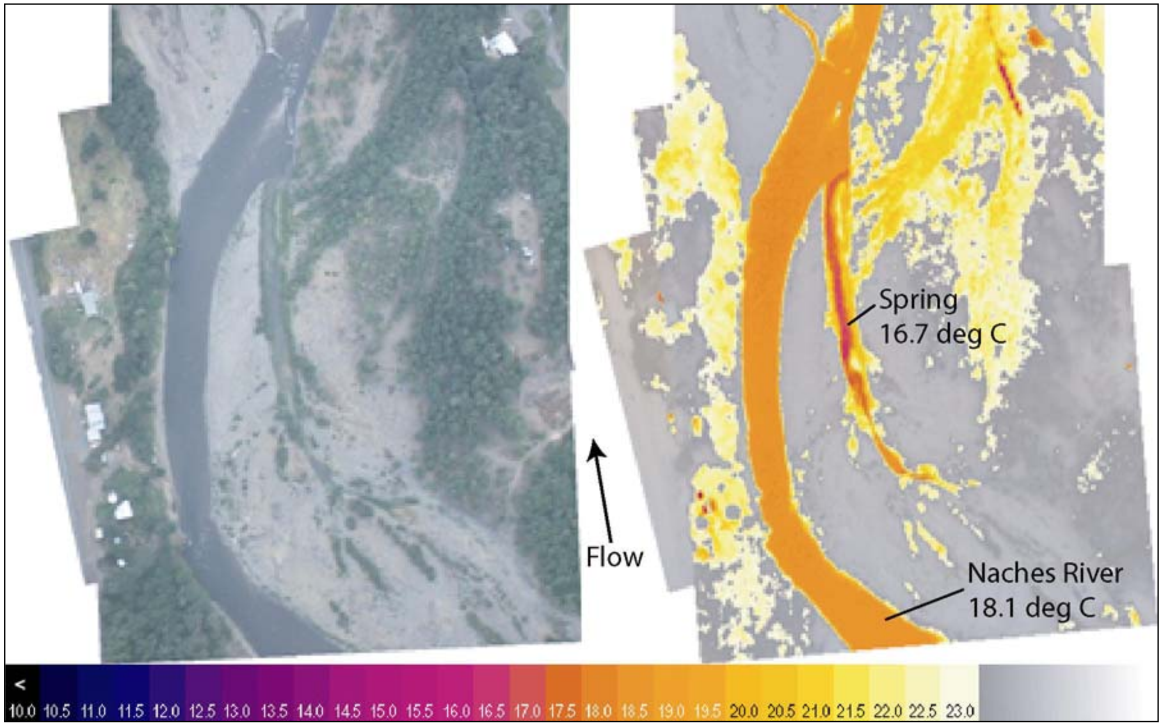
Springs (river mile 27.7)



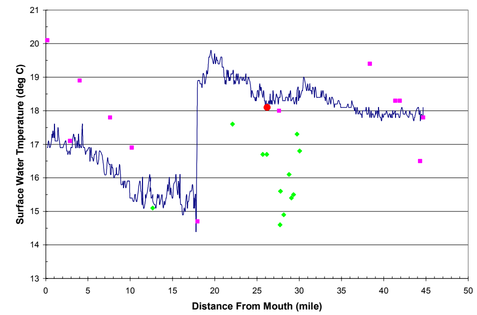
The image pair on the left shows a spring (16.3°C) on the left bank of the Naches River (18.4°C) at river mile 27.7. A second, smaller spring (14.6°C) can be seen along the right bank.



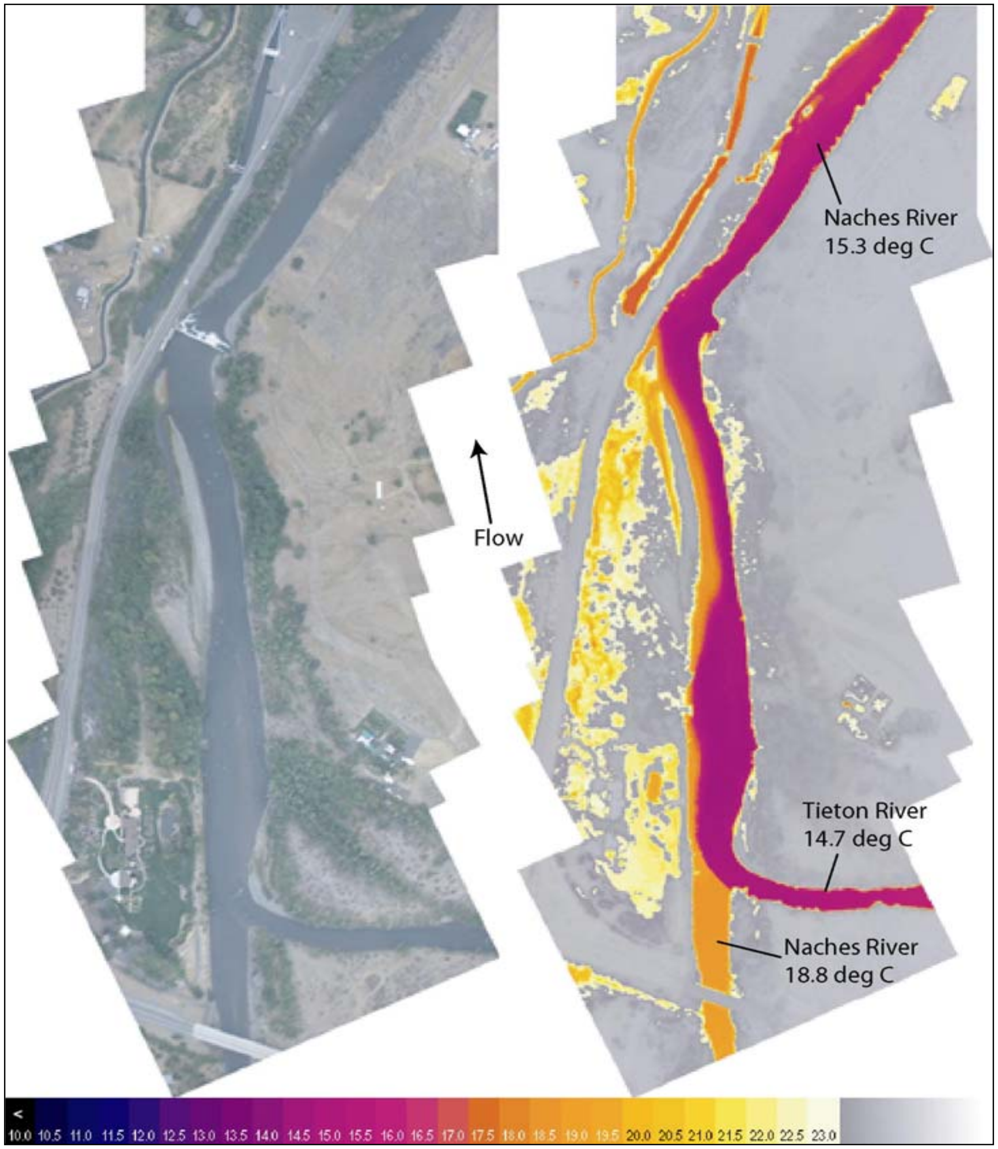
Springs (river mile 26.2)



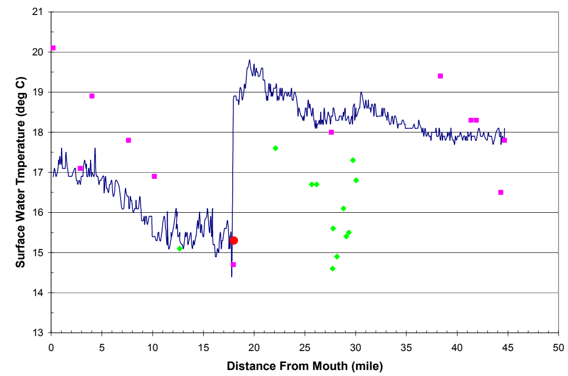
The image pair on the left shows a spring (16.7°C) along the right bank of the Naches River (18.1°C) at river mile 26.2.



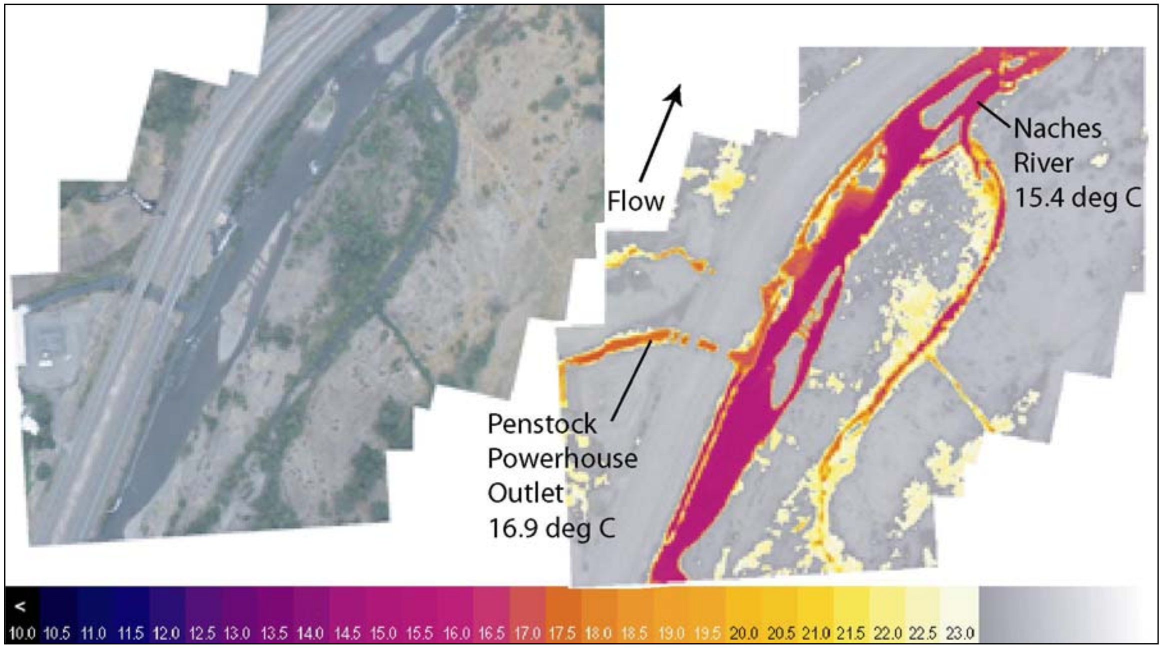
Tieton River Confluence (river mile 18.0)



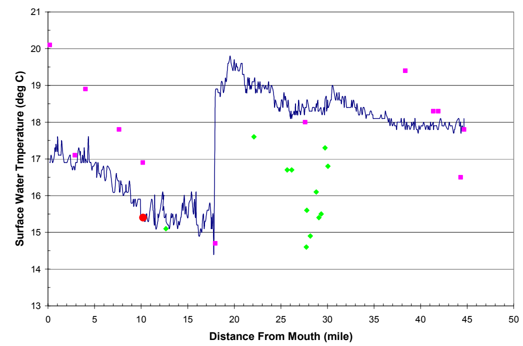
This image pair shows the confluence of the Tieton River (14.7°C) to the right bank of the Naches River (18.8°C) at river mile 18.0. The addition of the Tieton River to the Naches River decreased the main stem temperature by over 3°C to rest at 15.3°C downstream of the mixing zone.



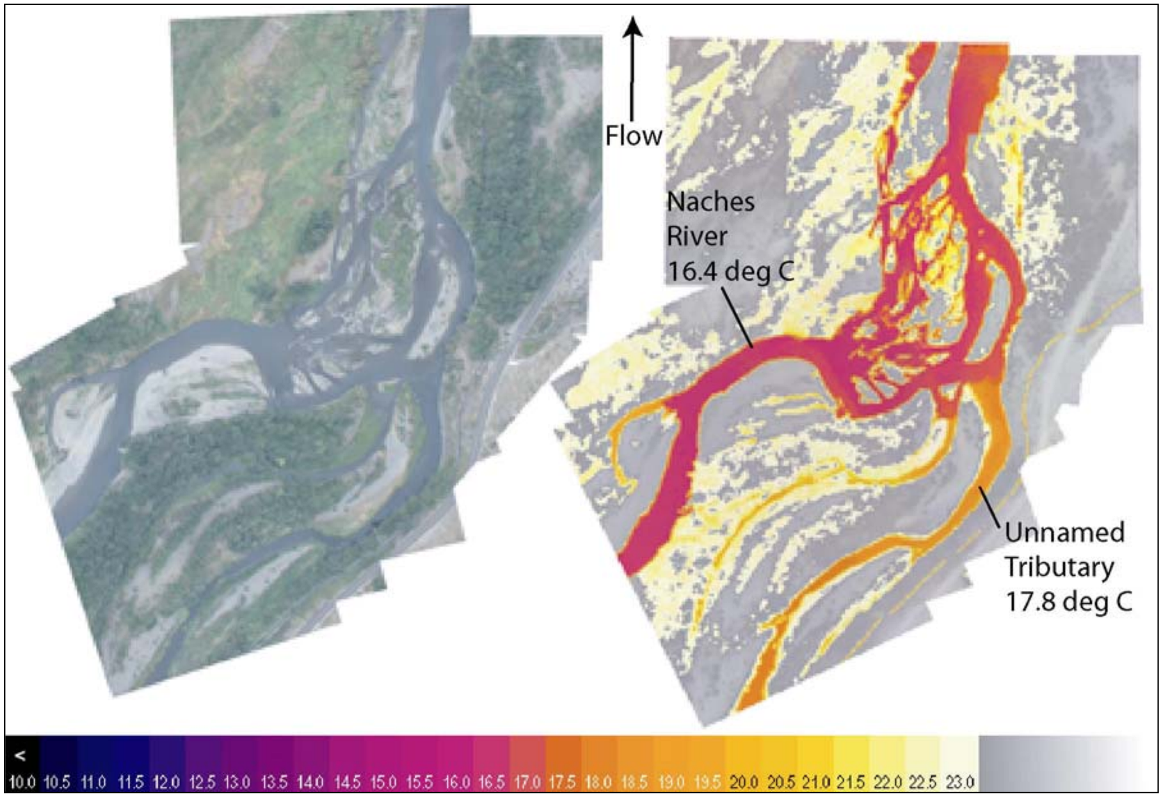
Penstock Powerhouse Outlet (river mile 10.2)



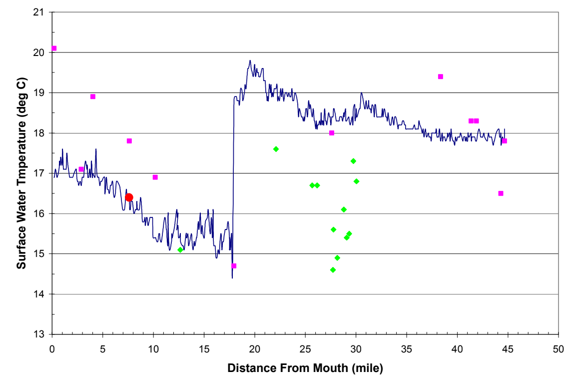
This image pair shows the addition of the Penstock Powerhouse outlet (16.9°C) to the main stem of the Naches River (15.4°C) at river mile 10.2.



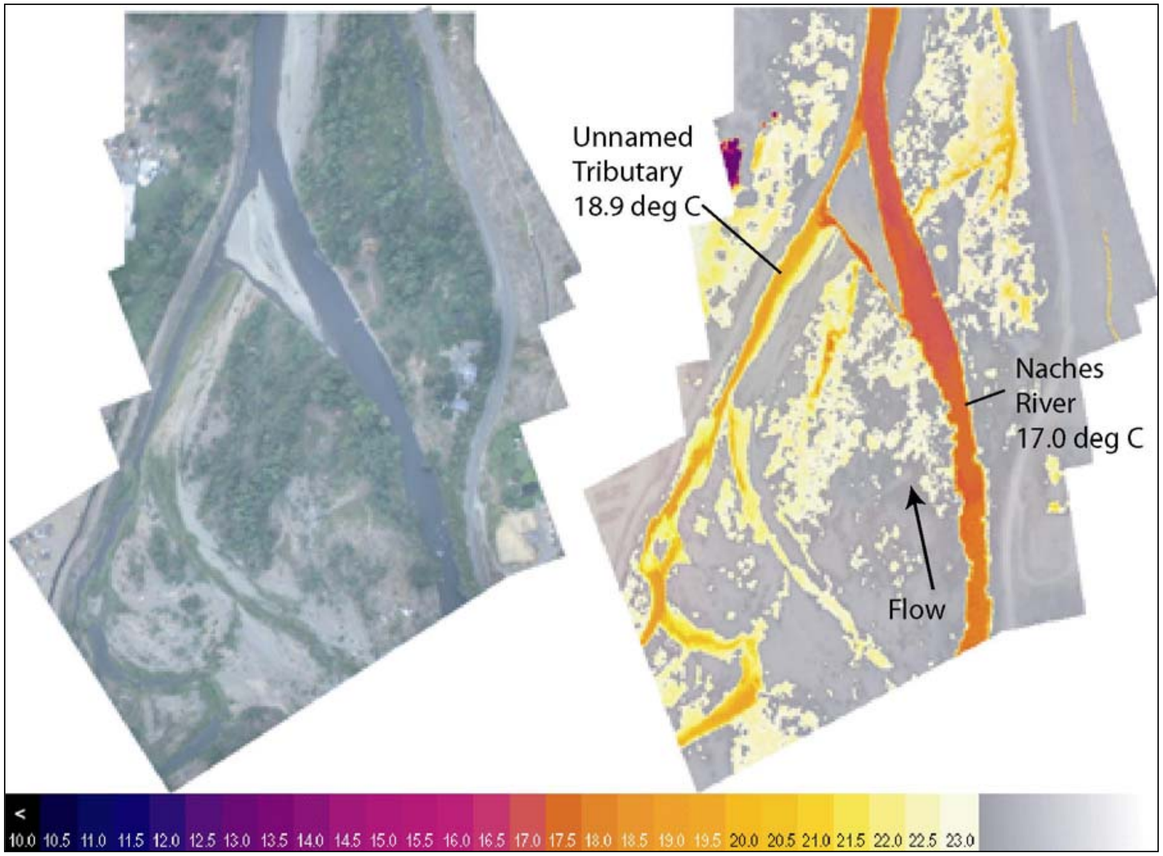
Unnamed Tributary Confluence (river mile 7.6)



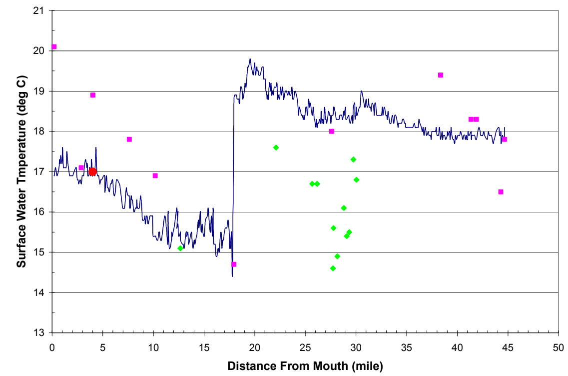
This image pair shows the confluence of an unnamed tributary (17.8°C) to the right bank of the Naches River (16.4°C) at river mile 7.6. The imagery also provides a good example of channel characteristics in this reach.



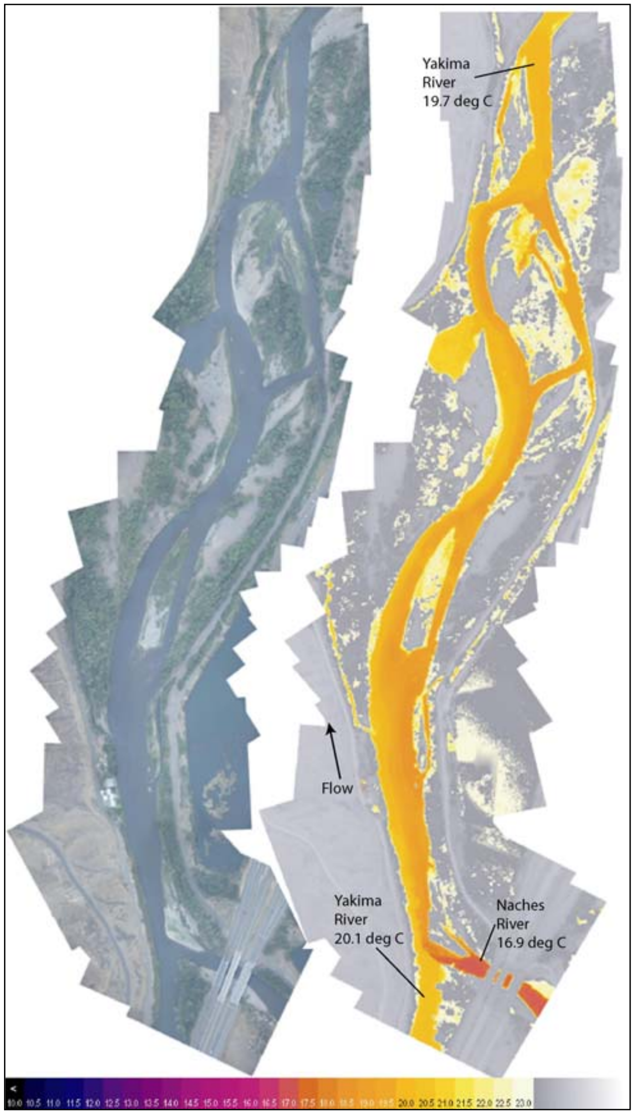
Unnamed Tributary Confluence (river mile 4.0)



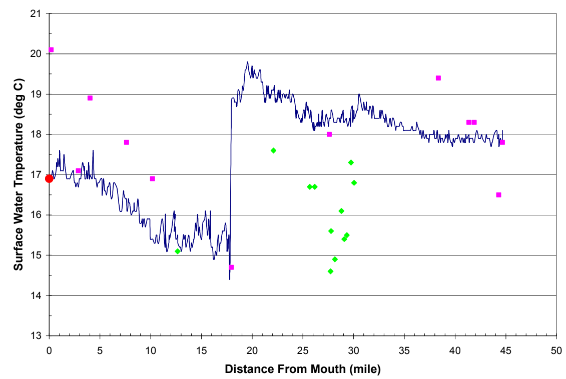
The image pair on the left shows the confluence of an unnamed tributary (18.9°C) on the left bank of the Naches River (17.0°C) at river mile 4.0.



Naches River Mouth



The image pair on the left shows the mouth of the Naches River (16.9°C) at the Yakima River (20.1°C), with the main stem Yakima River dropping to 19.7°C downstream of the mixing zone.



Summary of Survey Results

TIR images of the Naches River were successfully collected during the afternoon of August 14, 2004. The accuracy of the radiant temperatures was within specified values (i.e. ±0.5^{o}C) when compared to kinetic temperatures recorded by in-stream data loggers deployed prior to the flight.

The date of the flight was bracketed by forest fires early in the week and a prediction for poor weather on the weekend. The flight was conducted in warm, but progressively overcast conditions. The prediction for violent thunderstorms created the possibility for either increased flows and/or more fire strikes in the region. Although the conditions were acceptable, they were not ideal. It is likely that the increased cloud cover reduced the maximum daily temperatures from those observed earlier in the month. However, longitudinal temperature patterns should be consistent regardless of decreased air temperatures and reduced thermal loading. TIR surveys conducted on the same river in consecutive years have shown that, although absolute temperatures changed, the spatial temperature patterns of warming and cooling remained consistent (barring any significant management change). Sources of cooling and thermal loading remained relatively fixed. Although warmer conditions tend to exaggerate areas of heating, the general pattern remains the same. Follow-on analysis should examine how the temperature profile compares to in-stream maximums observed throughout the summer.

The TIR imagery and derived data sets provide a spatial context for analysis of seasonal temperature data from in-stream data loggers and for future deployment and distribution of in-stream monitoring stations. The TIR imagery directly illustrate the location and spatial extent of hyporheic discharge in the river. These areas of hyporheic exchange are very important for moderating temperatures during the summer months. This report provides some hypotheses on the processes influencing spatial temperature patterns at this scale, based on analysis of the TIR imagery. These hypotheses and observations are considered a starting point for more rigorous spatial analysis and fieldwork.

Individual TIR and color video image frames are organized in an ArcView database to allow for the viewing of temperature patterns and channel characteristics at finer spatial scales.